10.1071/AN11173_AC

Supplementary Material: *Animal Production Science* **53**(7–8), 806–816.

Supplementary Material

Simulating the impact of fertiliser strategies and prices on the economics of developing and managing the Cicerone Project farmlets under climatic uncertainty

Karl Behrendt[A,E], James M. Scott[B], Oscar Cacho[C] and Randall Jones[D]

[A] EH Graham Centre for Agricultural Innovation (Industry & Investment NSW and Charles Sturt University), Charles Sturt University, School of Agricultural and Wine Science, Wagga Wagga, NSW 2678, Australia.

[B] University of New England, School of Environmental and Rural Science, Armidale NSW 2351, Australia.

[C] University of New England, School of Economics, Armidale, NSW 2351, Australia.

[D] NSW Department of Industry & Innovation, Forest Road, Orange NSW 2800, Australia.

[E] Author for correspondence: email: kbehrendt@csu.edu.au

Introduction

The objective of the Dynamic Pasture Resource Development (DPRD) model is to provide a framework that is capable of simulating a dynamic pasture resource under stochastic climatic conditions. The methods applied and developed for the DPRD model simulate changes in botanical composition in response to stochastic pasture growth and its utilisation by grazing livestock. Within a Monte Carlo simulation framework this enables the investigation of the economics and risks associated with pasture improvement technologies, supplementary feeding and stocking rate policies.

The DPRD simulation model operates at the paddock level on a daily time step and contains 5 sub-models accounting for soil fertility, pasture growth, botanical composition, sheep meat and wool production, and economic performance. The method applied in the DPRD model incorporates two stages to modelling the change in pasture biomass within a season and between seasons. Figure 1 in

Behrendt *et al.* (2012b) illustrates a conceptual outline of the DPRD model at the paddock level and Table 1 here presents the major components of each of the sub-models.

In a single production year, four representative seasons have been identified that relate to tactical and strategic decision points within a grazing system, the biophysical characteristics of plant growth, and botanical composition change within the pastures. Within each season, pasture growth and consumption by grazing livestock operate on a daily time step. Between seasons, the relative areas occupied by desirable and undesirable species groups within the whole sward are modelled using exploited population growth modelling (Clark 1990). This descriptive simulation framework is used to investigate the expected production outcomes, economic performance and risks associated with fertiliser application and stocking rate policies over a 10 year planning horizon.

The DPRD model is parameterised using experimental simulation output from a complex mechanistic grazing systems model, *AusFarm* (CSIRO 2007). Such complex biophysical models that attempt to model biological systems as closely as possible, are not well suited to economic optimisation models (Cacho 1998), because of the time required to solve each simulation run. Hence there is a need to achieve a balance between complexity in the biophysical model and adequacy of information for improved decision making. Achieving this compromise was the primary reason for developing the DPRD model and its parameterisation with *AusFarm*. The *AusFarm* program was calibrated to field experimental data from the Cicerone Project's farming systems experiment.

Table 1: Major components of the sub-models

Sub-Model	Major Components
Soil Fertility	Soil P, fertility gain through fertiliser application, fertility lost through consumption and fixation
Pasture	Pasture mass, growth, quality and consumption
Pasture Composition	Pasture composition, intrinsic rate of population growth, impact of harvesting by livestock, and pasture establishment
Livestock	Selective grazing of sward between species groups, pasture and

	supplementary feed consumption, wool growth and quality, net balance of liveweight gain or loss
Economic	Seasonal value of production, seasonal costs of production including supplementary feeding and pasture sowing costs

Case Study: The Cicerone Project farmlet experiment

The Cicerone Project's farmlet experiment was set up to investigate the sustainability and profitability of three farm management systems on the Northern Tablelands of New South Wales (Scott *et al.* 2012; Sutherland *et al.* 2012). The experiment consisted of three farmlets, each of 53 hectares, which was conducted over the period July 2000 to December 2006. Farmlet A represented a higher input, flexible grazing system; Farmlet B represented a moderate input system with flexible grazing (described as typical district practice); and Farmlet C represented an intensive rotational grazing system with the same moderate inputs as the typical practice farmlet (B). Results from the experiment indicated that botanical composition in all of the farmlets changed in response to the level of system inputs and the imposed management (Shakhane *et al.* 2012).

The data available from the Cicerone Project farmlets, which included biophysical, managerial and economic data, provided a sound basis for the calibration of the *AusFarm* and DPRD models. The initial state of pasture and soil resources reported at the start of the Cicerone Project experiment formed the basis for the case study application of the bioeconomic framework in the high rainfall temperate pasture zone. Table 2 gives the estimated and reported values for parameters and constants introduced in each of the sub-models detailed.

Table 2: DPRD model parameters and constants

Parameter	Units	Value	Description
ρ		0.0494	Real Discount Rate calculated from inflation & nominal interest rate data plus margin (1.5%), over 1976 to 2006 (ABARE 2006)
β_{DP}		0.45	Sheep carcass:liveweight ratio

P_{SF}	\$/wet tonne	208.60	Cost of Supplements, mean feed wheat price 1997 to 2007 (ABARE 2007)
$SCOST$	\$/ha	250	Pasture sowing costs (Scott 2006)
VC	\$/hd/annum	15.68	Variable costs (Scott 2006)
$PCOST$	\$/ha/annum	20	Pasture & paddock maintenance costs
ρ_C		variable	Intrinsic rate of desirable population growth (*AusFarm* simulation, Hutchinson (*pers. comm.*) Scott (*pers. comm.*))
κ_C		0.95	Maximum population size of desirable species (proportion of paddock occupied)
λ_{SC}		variable	Seasonal livestock grazing impact co-efficient on desirable population (Cicerone Project & *AusFarm* simulation, Boschma and Scott (2000))
μ_C		2.5	Maximum utilisation constraint (*AusFarm* simulation, Scott (*pers. comm.*), Scott *et al.* (2000))
α_F		-0.09508	Derived from Gourley *et al.* (2007)
PBI		76	Average PBI for all Farmlets (Cicerone Database)
β_F		0.089	Proportion of phosphorus in single superphosphate (Glendinning 2000)
ζ_F	mg/kg colwell shift per kg P applied/ha	0.4313	Derived from Burkitt *et al.* (2001)
ι_F	mg/kg Colwell	3.0	Minimum slow release phosphorus from non-expendable pools (Jones *et al.* 2006; McCaskill and Cayley 2000)
ω_F	Kg P/kg clean wool	0.00026	Phosphorus content of wool (Glendinning 2000)
μ_F	Kg P/kg liveweight	0.006	Phosphorus content of liveweight (Glendinning 2000)

θ_F	Kg P/kg dung	0.007	Phosphorus content of dung (Helyar and Price 1999)
υ_F	Kg P in urine/kg total P excreted	0.01	Proportion of phosphorus in urine (Helyar and Price 1999)
o_F	Kg P	0.00685	Phosphorus lost in DM production (Helyar and Price 1999)
ρ_F	g/mm	1.5	Phosphorus content of rainfall (Helyar and Price 1999)
AR	mm/year	850	Average annual rainfall (Armidale NSW)
ε_F		0.83	Proportion of phosphorus in Colwell extract (Colwell 1963)
σ_F	g/cm^3	1.5	Soil Bulk Density (top 10cm)
σ_S	kg DM/kg liveweight	0.0115	Derived from Freer *et al.* (2007)

Economic Returns

In the DPRD simulation model, the economic sub-model assumes that a producer operating a wether enterprise aims to maximise the present value (*PV*) of the flow of seasonal gross margins over the planning horizon.

$$PV = \sum_{t=0}^{T} \left(A \sum_{s=1}^{S} GM_s \right) \delta^t \qquad (1)$$

where *PV* is the discounted present value of annual gross margins, *T* is the planning horizon in years, *t* is an index for year, *A* is the size of the paddock in hectares, *S* is the number of seasons in a year, *s* is an index for season, GM_s is the paddock's seasonal gross margin per hectare, and δ is the discount factor;

$$\delta = \frac{1}{(1+\rho)} \qquad (2)$$

where ρ is the real discount rate.

Seasonal returns

In calculating seasonal gross margins per hectare for a single paddock, the complexity of modelling flock structure and dynamics cannot be adequately incorporated due to the process of enterprise operation and livestock movements not being representative of a closed system within the paddock. Thus a simplified gross margin approach is used to define the seasonal value of production and its cost.

This approach assumes animals that enter the paddock operate in a steady state with no changes in their capital value from the start to the end of the season. However the method applied does allow for net liveweight change over a season. This enables the complex issue of flock structure and the particular types of animals that are used to harvest the pasture to be separated from the issue of optimising the quantities of pasture to be harvested.

A single paddock's seasonal gross margin per hectare, GM_s is calculated at the end of each season (s) as follows:

$$GM_s = SR(W_{INC} + M_{INC} - VC) - PCOST - SF_s P_{SF} - FCOST - SCOST \qquad (3)$$

where s is the index for season comprising a variable number of days, SR is the stocking rate decision variable (hd/ha), W_{INC} is the total value of wool produced in the season, M_{INC} is the total value of sheep meat grown in the season. The variable costs associated with each season are represented by VC and $PCOST$ which are the pro-rated variable costs and pasture costs dependent upon the length of the season (VC_t or $PCOST_t \cdot D_s/365$), the total quantity of supplements fed SF_s, and the cost of supplementary feed P_{SF}, the cost of any fertiliser applied $FCOST$, and any costs of sowing a new pasture in a season $SCOST$ ($/ha).

The total value of wool grown in any season, W_{INC}, is a function of the quantity of wool grown and its market value.

$$W_{INC} = P_{wool} \sum_{d=1}^{D_s} DW_d \qquad (4)$$

where P_{wool} is the market value or price of the wool produced ($/kg clean) which is a function of mean weighted fibre diameter, FD_s, of the wool produced in that season, and DW_d which is the amount of wool grown in each day (d) over the length of the season in days (D_s).

The total value of liveweight change in any season, M_{INC}, is calculated from the net balance of liveweight gain over the season and its market value.

$$M_{INC} = P_{meat}\beta_{DP}WT_s \tag{5}$$

where P_{meat} is the price of the sheep meat produced ($/kg carcass weight), WT_s is the net balance of liveweight gain or loss over a season (kg/hd), and β_{DP} is the dressing percentage for sheep.

The total quantity of supplements fed in a season (kg/ha) is the conversion of the sum of daily amounts fed in dry matter to wet tonnes.

$$SF_s = \frac{SR\sum_{d=1}^{D} SDM_d}{\alpha_S} \tag{6}$$

where SDM_d is the daily amount of supplement dry matter offered to grazing animals (kg DM/hd/d), SR is the stocking rate, and α_S is the dry matter to wet weight ratio for the supplement.

The cost of fertiliser applied per season is calculated from the amount of fertiliser applied. The impact of any fertiliser applied on residual soil fertility and promoting additional pasture growth, is assumed to occur in the season of application before accounting for maintenance phosphorus requirements.

$$FCOST_s = FERT_s\theta_{SF} \tag{7}$$

where $FERT_s$ is the amount of fertiliser applied in a season (kg of SS/ha), and θ_{SF} is the cost per kilogram of fertiliser.

Incorporation of risk

Risk was incorporated into the model by representing climatic variability using Monte Carlo simulations. The method is based on using stochastic multipliers in pasture equations as explained in the following sections. The 10-year Monte Carlo simulations of the DPRD model reported in Behrendt *et al.* (2012b) are used to derive risk-efficient frontiers (Cacho *et al.* 1999).

Botanical composition of the pasture resource

In mechanistic pasture or crop models, botanical composition is generally modelled on the assumption of competitive interference for resources such as water, light and occasionally nutrients. But this method does not cope well with simulating more than two competing pasture species. Furthermore, there is the underlying assumption in some models that species persist indefinitely and homogeneously occupy space within the sward. Rather than modelling explicitly how plants interact, the response of plants to changes in their environment can be represented by the net ability of a group of plants to capture resources and compete (Kemp and King 2001).

The empirical pasture composition sub-model within the DPRD model adapts the 'partial paddocks' method proposed by Loewer (1998). In Loewer's GRAZE model it is assumed that each species is uniformly distributed throughout a paddock and that the initial area they occupy remains fixed. However, the dry matter availability of each species is varied through selective grazing and independent species growth. In the DPRD model the space occupied by species is assumed to be variable and respond to climate, management and inputs.

The total area of pasture is comprised of two components, Desirable species and Undesirable species so that $X_D + X_U = 1.0$, where X_D is the proportion of desirable species and X_U is the proportion of undesirable species within the pasture sward. This is a spatial measure of sward composition similar to basal measurement common in agronomic experiments (Whalley and Hardy 2000), with the empirical modelling approach adopted similar to the methods used for basal area adjustments applied in some rangeland models (Stafford Smith *et al.* 1995).

The population of desirable species in the sward is modelled by using differential equations describing population growth and the impact of harvesting. These represent the pasture resource as an exploitable renewable resource as described by Clark (1990). In this application to the renewable resource of desirable species, the equations are in the form:

$$\frac{dX_D}{ds} = F(X_D) - h(s) \tag{8}$$

where $X_D = X_D(s)$ denotes the proportional area occupied by desirable species within a sward, $F(X_D)$ represents the rate of growth in the area of desirable species, and $h(s)$ is the impact of harvest or grazing on the area occupied by desirable species in season *s*.

The rate of growth in the area of desirable species under limited spatial and environmental resources is described using a logistic growth model:

$$F(X_D) = \rho_C X_D \left(1 - \frac{X_D}{\kappa_C FE}\right) FE \qquad (9)$$

where ρ_C is the intrinsic rate of growth in the area occupied by desirables species, and κ_C is the environmental carrying capacity, or the maximum area of the paddock that the desirable species may occupy within a sward. The introduction here of a soil fertility effect (*FE*), affects both the rate of growth in the population and the potential size of the population (Cook *et al.* 1978; Dowling *et al.* 1996; Hill *et al.* 2005).

The parameter ρ_C is subject to $0 < \rho_C < 1.0$, and is variable as it relates to climate and season. This parameter is varied depending on the type of year and the season in which the shift in botanical composition is being modelled. Higher ρ_C values are expected in favourable years where climatic conditions favour vegetative growth and reproduction of desirable species and lower ρ_C values are expected under poorer climatic conditions.

To enable the application of this method on a seasonal basis, the values of ρ_C for a particular year type have been made in proportion to the potential for vegetative growth and reproduction in a season. Values for ρ_C were estimated from the simulation and analysis of field experimental data.

The effect of any livestock grazing on sward structure, *h(s)*, is estimated using the predicted utilisation by grazing livestock of the pasture grown in a season. This takes into account both of the components that make up grazing pressure on the sward, namely stocking rate and grazing time, and the stochastic growth of the pasture in a season.

$$h(s) = UX_D \lambda_{SC} \qquad (10)$$

where UX_D is the utilisation of the desirable pasture grown in a season by grazing livestock, and λ_{SC} is the impact coefficient of grazing livestock on the population of desirable species components within the sward. The measure UX_D is similar in principle to the measure of grazing pressure defined by Doyle *et al.* (1994). The parameter λ_{SC} is positive and variable as it relates to the time of year in which the shift in botanical composition is being modelled. The value of the parameter reflects the sensitivity of botanical composition change to seasonal grazing pressure on species phenology.

Typically the harvesting effect is based on the concept of *catch-per-unit-effort* where the harvest is linearly proportional to the size of the population (Clark 1990). This has been modified in this application of the model due to the way pasture utilisation by grazing livestock is estimated.

$$UX_D = \max\left(\mu_C, \frac{\sum_{d=1}^{D} PC_{Dd}}{\sum_{d=1}^{D} PG_{Dd}}\right) \tag{11}$$

where μ_C is the maximum utilisation constraint on the impact of grazing livestock on the population of desirables species, PC_D is the quantity of dry matter consumed from only the desirable components of the sward (kg DM/ha), and PG_D is the quantity of dry matter grown from the desirable components of the sward (kg DM/ha). As utilisation over a season is calculated based on the consumption and growth of individuals in the population of desirable species, the need to make *h(s)* a function of X_D is removed. Thus *h(s)* remains constant across all states of botanical composition.

This empirical method encapsulates the concept of state and transition models of rangelands (Westoby *et al.* 1989), with the benefit of an indefinite number of pasture states and responses to climate, grazing and input factors.

Pasture growth

Pasture growth is based on the sigmoidal pasture growth curve of Cacho (1993). Here the individual growth of pasture biomass (kg DM/ha/d) for desirable and undesirable species is calculated as follows (excluding *U* and *D* subscripts for notational convenience):

$$PG = \alpha_G \frac{Y^2}{Y_{\max}} \left[\frac{Y_{\max} - Y}{Y}\right]^{\gamma_G} FE \tag{12}$$

where α_G is a growth parameter influenced by the soil fertility effect (*FE*) and climate under stochastic simulations, Y_{max} is the maximum sustainable herbage mass or ceiling yield when an equilibrium is reached between new growth and the senescence of old leaves (but excluding the decay of plant material), γ_G is a dimensionless parameter with a value in the range of $1< \gamma_G <2$ (Cacho 1993). The parameters were estimated using simulation output from *AusFarm* (Moore 2001) which was calibrated to experimental data from the Cicerone Project farmlets, and are presented in Behrendt *et al.* (2012a).

To incorporate stochastic climatic conditions, α_G and γ_G are adjusted seasonally to reflect different year types using stochastic multipliers. As described in Cacho *et al.* (1999), the mean seasonal α_G and γ_G parameters used under deterministic simulations are multiplied by their respective stochastic multiplier. These stochastic multipliers, *SMα* and *SMγ*, are defined for season *i* and year *t* as follows;

$$SM\alpha_{it} = \frac{\alpha_{it}}{\frac{1}{n}\sum_t \alpha_{it}} \text{ and } SM\gamma_{it} = \frac{\gamma_{it}}{\frac{1}{n}\sum_t \gamma_{it}} \tag{13}$$

where *n* is the number of years in the sample from which the parameters are derived. During the running of a stochastic simulation these stochastic multiplier values are randomly selected in sets of annual cycles or year types from a uniform distribution. Given that the parameters for each year type have been derived from years simulated using *AusFarm*, each year has the same probability of being selected.

Soil fertility

The soil fertility sub-model is similar in nature to the concept of fertility scalars used in more complex biophysical models of grazing systems (Moore *et al.* 1997), but with the index limiting pasture growth at a daily time step as described in Cacho (1998), as well as affecting both the rate of growth in the desirable population and its potential population size. This occurs through the inclusion of FE_s in equations (12) and (9) respectively.

The soil fertility effect for a season, FE_s, is based on the soil phosphorus levels carried over from the previous season and any increases in soil phosphorus from the application of fertiliser. The relative yield restriction is estimated using the Mitscherlich equation (Thornley and France 2007).

$$FE_s = 1 - e^{\alpha_F P_s} \tag{14}$$

where P_s is the level of soil phosphorus at the start of a season (mg/kg Colwell (Colwell 1963)) and α_F is the parameter describing the rate of change in relative yield response to changes in the levels of soil phosphorus. The parameter α_F is an estimated value which solves equation (14) when the relative yield or fertility effect (FE_s) equals 0.95 and P_s equals P_{CF}. P_{CF} is the predicted critical Colwell phosphorus level (P_{CF}) at which 95% of maximum relative yield occurs. P_{CF} is estimated using the following published function derived from the Better Fertiliser Decisions national database (Gourley *et al.* 2007).

$$P_{CF} = 19.6 + 1.1PBI^{0.55} \qquad (15)$$

where *PBI* is the Phosphate Buffering Index of a representative soil derived from the Cicerone Project farmlets database.

Changes to the level of soil phosphorus between seasons are a function of the amount of fertiliser applied and the grazing systems maintenance fertiliser requirements. The level of soil phosphorus for the current season *s*, is calculated after taking into account any applications of fertiliser, whereas the level of soil phosphorus entering the next season, $s+1$, is net of the maintenance phosphorus requirements. This assumes there is an immediate response in pasture growth to any fertiliser applied in the current season, although the residual phosphorus pool for the following season is reduced due to maintenance phosphorus requirements over the season. After the application of fertiliser, the phosphorus level for the current season is calculated as follows:

$$P_s = \max\left[\iota_F, P_{s-1} + \zeta_F\left(P_{FERT}\beta_F\right)\right] \qquad (16)$$

where P_{s-1} is the soil phosphorus level at the start of the season (mg/kg Colwell), and P_{FERT} is the amount of fertiliser applied (kg of single superphosphate applied/ha). β_F is the proportion of phosphorus available in the fertiliser, ζ_F is a constant that allows for the phosphate buffering capacity of the soil and the response of soil phosphorus levels to applications of fertiliser derived from Burkitt *et al.* (2001), and ι_F is the minimum amount of slow release phosphorus from non-expendable pools available for plant growth.

The amount of soil phosphorus remaining at the end of the season is calculated net of maintenance phosphorus requirements, as follows:

$$P_{s+1} = \max\left(\iota_F , P_s - P_{main}\right) \tag{17}$$

where P_{main} is the maintenance fertiliser requirement. The estimation of maintenance fertiliser requirements is derived from the relationships described in Helyar and Price (1999). P_{main} (in mg/kg soil) is a function of phosphorus losses from the paddock system due to livestock product exports and removal of soil phosphorus to sheep camps, and the accumulation of non-exchangeable inorganic and organic phosphorus reserves, and phosphorus gains from non-fertiliser inputs.

$$P_{main} = \frac{\varepsilon_F \left(P_{Exp} + P_{DU} + P_{Acc} - P_{NF}\right)}{\sigma_F} \tag{18}$$

where P_{Exp} is the quantity of phosphorus removed through livestock products (kg P/ha), P_{DU} is the removal of soil phosphorus to sheep camps, P_{Acc} is the accumulation of non-exchangeable organic phosphorus, P_{NF} is the non-fertiliser inputs to soil phosphorus levels, ε_F is the proportion of exchangeable phosphorus extracted in the Colwell soil test, and σ_F is the bulk density of the top 10cm of soil (g/cm^3). P_{Exp} is calculated from the amount of product, both wool and sheep meat, removed during the season.

$$P_{Exp} = SR\left\lfloor \omega_F \sum_{d=1}^{D} DW_d + \mu_F WT_s \right\rfloor \tag{19}$$

where DW_d is the daily growth of wool per head, WT_s is net liveweight gain or loss per head, with ω_F and μ_F being the proportion of phosphorus in wool and sheep meat. The calculation of the amount of phosphorus removed through dung and urine to sheep camps, P_{DU}, is based on an assumed constant rate of dung and urine removal per grazing animal.

$$P_{DU} = \frac{\theta_F \sum_{d=1}^{D} 0.1SR}{\left(1 - \upsilon_F\right)} \tag{20}$$

where θ_F and υ_F are the proportions of phosphorus in dung and urine that are relocated and concentrated into sheep camps. The quantity of phosphorus immobilised in non-exchangeable organic phosphorus pools is related to pasture production:

$$P_{Acc} = \sum_{d=1}^{D} o_F \left(\frac{\left(PG_U X_U + PG_D X_D\right)}{20.5} \right)_d \tag{21}$$

where o_F is the proportion of phosphorus accumulated in the largely non-exchangeable organic phosphorus pool. The non-fertiliser inputs to soil phosphorus, P_{NF} (kg P/ha/season), are based on the quantity of phosphorus in average rainfall.

$$P_{NF} = \sum_{d=1}^{D} \frac{\rho_F AR}{3.65 \times 10^5} \tag{22}$$

where AR is the mean annual rainfall (mm/year), and ρ_F is the amount of phosphorus in rainfall (g/mm).

Livestock Production

A mechanistic approach is applied in the DPRD livestock sub-model, with much of it based on the equations used in the *GrazPlan* suite of models (Donnelly *et al.* 1997; Freer *et al.* 2007). This was required to ensure there were adequate feedback mechanisms between the selective grazing by livestock and changes in botanical composition.

In this sub-model, grazing sheep are capable of selectively grazing between the desirable and undesirable partial paddocks and between the digestibility pools of dry matter available to them within each partial paddock. This selective grazing is based on the assumption that grazing sheep will aim to maximise their intake based on the dry matter digestibility of plants. Such models, that base diet selection between species or species groups on the digestibility of the dry matter, have been validated by research into the influence of pasture degradation on diet selection and livestock production (Chen *et al.* 2002). Supplementary feeding is also available as a means of substituting for the consumption of pasture dry matter.

Supplementary feeding policies

Two feeding decision rules are applied in the Monte Carlo simulation framework (Table 3).

These decision rules are applied each day in the model with the equivalent of a maintenance ration of cereal grain (wheat) being offered to the grazing animals when applicable. The quantity of supplements offered to grazing animals, kg DM/animal/day, is calculated using the following equation.

$$SDM = 0.85 SRW \sigma_S \tag{23}$$

where *SRW* is the standard reference weight of the sheep genotype in condition score 3.0, σ_S is the quantity of supplement required to maintain 1kg of liveweight of a sheep in condition score 2.0 (Freer *et al.* 2007).

Table 3: Supplementary feeding decision rules applied in the DPRD model with the quantity offered being *SDM*.

Supplementary feeding rule	Description
If $B_d < 0.85SRW$	Represents a minimum condition score of 2.0 at which wethers are capable of survival and production, and have a reduced likelihood of producing tender wool (Bell and Alcock 2007; Morley 1994). This base feeding rule is applied concurrently with the following pasture mass driven feeding rule.
If $\sum_{dp=1}^{6} GTotal_{dp} < 100$	Minimal supplementation to maintain the existence of a pasture sward in the DPRD model.

References

ABARE (2006) 'Australian Commodity Statistics 2006.' (Australian Bureau of Agricultural and Resource Economics: Canberra). 354 pp.

ABARE (2007) 'Australian Commodity Statistics 2007.' (Australian Bureau of Agricultural and Resource Economics: Canberra). 354 pp.

Behrendt K, Cacho O, Scott JM, Jones RE (2012a) Optimising pasture and grazing management decisions on the Cicerone Project Farmlets over variable time horizons *Animal Production Science* **This edition**.

Behrendt K, Cacho O, Scott JM, Jones RE (2012b) Simulating the impact of fertiliser policies and prices on the economics of developing and managing the Cicerone Project Farmlets under climatic uncertainty. *Animal Production Science* **In Press**.

Bell A, Alcock D (2007) Full hand feeding of sheep - management. NSW DPIPrimeFact 345.

Boschma SP, Scott JM (2000) Measuring and predicting the consequences of drought for a range of perennial grasses on the Northern Tablelands of New South Wales. *Australian Journal of Experimental Agriculture* **40**, 285-297.

Burkitt LL, Gourley CJP, Sale PWG, Uren NC, Hannah MC (2001) Factors affecting the change in extractable phosphorus following the application of phosphatic fertiliser on pasture soils in southern Victoria.(Statistical Data Included). *Australian Journal of Soil Research* **39**, 759.

Cacho O (1998) Solving bioeconomic optimal control models numerically. In 'Proceedings of the bioeconomics workshop. Post-Australian Agricultural and Resource Economics Society conference, University of New England, Armidale, New South Wales'. Canberra Australia. (Ed. J Gooday) pp. 13-26. (Australian Bureau of Agricultural and Resource Economics (ABARE), Canberra).

Cacho OJ (1993) A practical equation for pasture growth under grazing. *Grass and Forage Science* **48**, 387-394.

Cacho OJ, Bywater AC, Dillon JL (1999) Assessment of production risk in grazing models. *Agricultural Systems* **60**, 87-98.

Chen W, Scott JM, Blair GJ, Lefroy RDB, Hutchinson KJ, King KL, Harris C (2002) Diet selection and sheep productivity of sheep grazing contrasting pastures. *Australian Journal of Agricultural Research* **53**, 529-539.

Clark CW (1990) 'Mathematical bioeconomics: the optimal management of renewable resources.' (John Wiley and Sons Inc.: New York USA).pp.

Colwell JD (1963) The estimation of the phosphorus fertilizer requirements of wheat in southern New South Wales by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry* **3**, 190-197.

Cook S, Blair G, Lazenby A (1978) Pasture degeneration. II. The importance of superphosphate, nitrogen and grazing management. *Australian Journal of Agricultural Research* **29**, 19-29.

CSIRO (2007) AusFarm. (CSIRO Plant Industry).

Donnelly JR, Moore AD, Freer M (1997) GRAZPLAN: decision support systems for Australian grazing enterprises-I. Overview of the GRAZPLAN project, and a description of the MetAccess and LambAlive DSS. *Agricultural Systems* **54**.

Dowling PM, Kemp DR, Michalk DL, Klein TA, Millar GD (1996) Perennial Grass Response to Seasonal Rests in Naturalised Pastures of Central New South Wales. *The Rangeland Journal* **18**, 309-326.

Doyle PT, Grimm M, Thompson AN (1994) Grazing for Pasture and Sheep Management in the Annual Pasture Zone. In 'Pasture Management: Technology for the 21st Century'. (Eds DR Kemp, DL Michalk) pp. 71-90. (CSIRO: East Melbourne).

Freer M, Dove H, Nolan JV (Eds) (2007) 'Nutrient Requirements of Domesticated Ruminants.' (CSIRO Publishing: Collingwood).

Glendinning JS (2000) 'Australian Soil Fertility Manual.' (Fertilizer Industry Federation of Australia, Inc & CSIRO Publishing: Collingwood). 154 pp.

Gourley CJP, Melland AR, Waller RA, Awty IM, Smith AP, Peverill KI, Hannah MC (2007) Making Better Fertiliser Decisions for Grazed Pastures in Australia. Department of Primary Industries Victoria, Melbourne.

Helyar KR, Price GH (1999) Making recommendations based on soil tests. In 'Soil Analysis an Interpretation Manual'. (Eds KI Peverill, LA Sparrow, DJ Reuter) pp. 331-357. (CSIRO Publishing: Collingwood).

Hill JO, Simpson RJ, Wood JT, Moore AD, Chapman DF (2005) The phosphorus and nitrogen requirements of temperate pasture species and their influence on grassland botanical composition. In 'Australian Journal of Agricultural Research' pp. 1027-1039).

Hutchinson K (*pers. comm.*) Honorary Fellow pp. Department of Agronomy and Soil Science, School of Environmental and Rural Science, The University of New EnglandArmidale).

Jones RE, Dowling PM, Michalk DL, King WM (2006) Sustainable grazing systems for the Central Tablelands of New South Wales. 5. A bioeconomic framework for assessing the long-term economic benefits of grazing management tactics and implications for sustainability. *Australian Journal of Experimental Agriculture* **46**, 495-502.

Kemp DR, King WM (2001) Plant Competition in Pastures - Implications for Management. In 'Competition and succession in pastures'. (Eds PG Tow, A Lazenby) pp. 85-102. (CABI Publishing: Wallingford).

Loewer OJ (1998) GRAZE: A Beef-Forage Model of Selective Grazing. In 'Agricultural Systems Modeling and Simulation'. (Eds RM Peart, BR Curry) pp. 301-418. (Marcel Dekker, Inc.: New York).

McCaskill MR, Cayley JWD (2000) Soil audit of a long-term phosphate experiment in south-western Victoria: total phosphorus, sulfur, nitrogen, and major cations. *Australian Journal of Agricultural Research* **51**, 737-748.

Moore AD (2001) FarmWi$e: a flexible decision support tool for grazing systems management. In 'Proc. XIX International Grassland Congress'. SÃO PAULO, BRAZIL. (International Grassland Congress).

Moore AD, Donnelly JR, Freer M (1997) GRAZPLAN: Decision Support Systems for Australian Grazing Enterprises. III. Pasture Growth and Soil Moisture Submodels, and GrassGro DSS. *Agricultural Systems* **55**, 535-582.

Morley FHW (1994) Drought Prediction and Budgets. In 'Merinos, Money & Management'. (Ed. FHW Morley) pp. 249-262. (Post Graduate Committee in Veterinary Science, University of Sydney: Sydney).

Scott JF (2006) An Economic Comparison of Sheep Grazing Systems on the Northern Tablelands of NSW. Master of Economics, The University of New England. 170 pp.

Scott JM (*pers. comm.*) Professor pp. Department of Agronomy and Soil Science, School of Environmental and Rural Science, The University of New EnglandArmidale).

Scott JM, Gaden CA, *et al.* (2012) Experimental treatments and management guidelines for comparing and measuring three grazed farmlet systems. *Animal Production Science* **52**, (in press).

Scott JM, Hutchinson KJ*, et al.* (2000) Quantifying the sustainability of grazed pastures on the Northern Tablelands of New South Wales. *Australian Journal of Experimental Agriculture* **40**, 257-265.

Shakhane LM, Murison RD, Mulcahy C, Scott JM, Hinch GN, Mackay D, Morrow A (2012) Changes in botanical composition on three farmlets subjected to different pasture and grazing management strategies. *Animal Production Science* **52**, (in press).

Stafford Smith DM, Milham N, Douglas R, Tapp N, Breen J, Buxton R, McKeon G (1995) Whole Farm Modelling and Ecological Sustainability: a Practical Application in the NSW Rangelands. In 'Proceedings of the Conference from the Australian and New Zealand Society of Ecological Economics' pp. 243-249.

Sutherland H, Scott JM, Gray D, Woolaston R (2012) Creating the Cicerone Project: seeking closer engagement between livestock producers, research and extension. *Animal Production Science* **52**, (in press).

Thornley JHM, France J (2007) 'Mathematical Models in Agriculture: Quantitative Methods for the Plant, Animal and Ecological Sciences.' (CABI: Wallingford). 906 pp.

Westoby M, Walker B, Noy-Meir I (1989) Opportunistic management for rangelands not at equilibrium. *Journal of Range Management* **42**, 266-274.

Whalley RDB, Hardy MB (2000) Measuring botanical composition of grasslands. In 'Field and laboratory methods for grassland and animal production research' pp. 67-102. (CABI Publishing: Wallingford UK).